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DEVELOPMENT AND CALIBRATION OF A PEDAL WITH FORCE AND MOMENT SENSORS

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Abstract—**An instrumented bicycle pedal was built and calibrated. The pedal has good linearity and sensibility, comparable to other instruments in the literature.**

I. INTRODUCTION

Several equipments have been developed in the last decades for the measurement of the force applied on pedals during bicycling and bicycle ergometer tests. The vast majority of pedals were bi-axial, which do not allow a complete evaluation of the forces and moments in the three axis (x, y and z) [1]. This has been considered a huge limitation in Brazil, since there is no tri-axial pedal available in the Brazilian market for clinical application and research use [2, 3, 4, 5, 6, 7, 8].

One important and delicate aspect in the process of developing a three-axial pedal is its calibration. This study aimed to perform accurate calibration of a tri-axial pedal, including forces applied, deformations, nonlinearities, hysteresis and standard error for each axis. Calibration was based on Hull and Davis method [2], which is based on the application of known loads on the pedal in order to create a calibration matrix.

Material and Methods

System development

The development of a three-axial pedal considered the following aspects: to be a simple, low cost instrument, to be able to measure the forces and moments in the three axes (x,y,z), to be similar to the ones found in the literature, to have a potential for commercialization. The pedal was therefore based on strain gauges of variable electrical resistance, which made it simpler and less expensive. The project was designed with SolidWorks® software, which allowed a 3D visualization of the pedal.

The material used was aluminum alloy AA 6351 T6, (elasticity module70GPa and 0,45% deformation resistance), which was used by Neto et al. [9]. The prototype was submitted to finite element analysis using the Promechanica® software. The project aimed to use the smallest possible number of Strain gauges. We used a total of 4 full Wheatstone bridges and 4 half bridges, adding up 24 Strain gauges. The size of the pedal was required to be similar to a commercial pedal, but the structure is taller so that it has measurable deformation in the z axis.

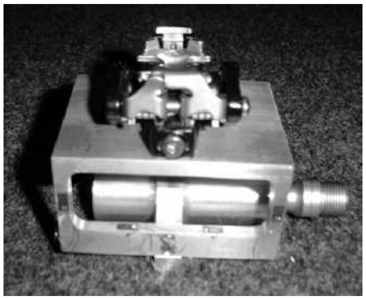

Figure 1 : pedal prototype with strain gauges.

Calibration

The procedure started with calibrating masses in the range 10-65N, using a 4 digit scale (Filizola®).

The next step was the fixation of the pedal such that it was possible to impose uniaxial moments and forces in the three axis. After the fixation, the loads were applied, and the data were acquired using the CIO-DAS-08 board and software SAD2. The loads were added one by one, in 15s intervals. The same protocol was used for unloading. After measuring each axis, the pedal was turned around and measured in the opposite direction. The procedure was repeated for each axis. For imposition of traction, a steel cable and a basket were used, and each axis was tested.

A mechanical torquimeter with 5% precision was used for the calibration of moments (Smalcalda, GDR). A steel cable and an adjustment bolt were used for controlling the calibration essay.

The data were processed in the SAD2 software.

The channels were summed according to the methodology used by Hull and Davis [2], as stated in equation 1.

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$$V_{fx} = (p0 + p1)$$
$$V_{fy} = (p2 + p3)$$
$$V_{fz} = (p4 + p5 + p6 + p7)$$
$$V_{mx} = (p4 + p5 - p6 - p7)$$
$$V_{my} = (p4 - p5 - p6 + p7)$$
$$V_{mz} = (-p3 - p1 + p2 + p0)$$

Equation 1 - Channel sum method.

The channels were then filtered using a weighted moving average filter with cutout frequency of 10Hz [10].

The next step was the separation of plateaus for each step and the averaging of these values. A table with the values measured for each axis with each weight was created. Microsoft Office Excel 2003 was used to calculate the linear regression for the values of load and unload of each force and moment elements of each axis. This resulted in the angular coefficient [11] which is used to build the calibration matrix [12]. The sensitivity, histeresis and nonlinearity of each axis were calculated.

Results

The calibration matrix was calculated from the angular coefficients of the sensors (Tables 1 and 2).

Table 1- Calibration matrix for force components.

Axis	Fx	Fy	Fz
VFx	2.305545	0.69764	2.150643
VFy	3.818218	23.02944	3.345276
VFz	5.953698	0.252686	11.31874
VMx	11.42963	-13.9355	-10.5279
VMy	-15.327	-30.3192	-11.3967
VMz	-29.6927	-1.1671	9.403679

Table 2- Calibration matrix for moment components.

Axis	Mx	My	Mz
VFx	0.383426	-24.4571	-0.1486
VFy	5.142841	0.165182	3.113405
VFz	0.613059	0.438767	-4.3577
VMx	233.7472	13.61461	-99.4366
VMy	11.03453	285.5557	31.05645
VMz	-16.3764	-117.615	10.16588

Discussion

Forces and moments in the z axis are highly linear. This is not true for moment My and force in the y axis, although the variation in these axis is small. The largest variation occurred in the z axis (7709.00215mV). We obtained the sensitivity of 11.319mV/N and resolution of 0.4313N with the selected 12 bit A/D converter. The z axis presented values of 1.201904% for histeresis and 2.812607% for nonlinearity. The values of angular coefficients of linear regressions were used for building the third line of the calibration matrix.

In the y axis, all forces and moments were highly linear, except for My. The y axis presented the largest variation of all axis, 15694.7869mV. This resulted in a sensitivity of 23.02944mV/N and a resolution of 0.2120N. The y axis had a value of 3.229819% for histeresis and 2,58193% for nonlinearity. The values of angular coefficients of linear regressions were used for building the second line of the calibration matrix.

For calibration in x axis, all forces and moments had high linearity, except Mz and Mx. My presented the largest variation of all axis. The x axis presented a variation of 1618.39938mV. This resulted in a sensitivity of 2.3055mV/N and a resolution of 2.1178N. The x axis had a value of 18.994793% for histeresis and 7.08058% for nonlinearity. The values of angular coefficients of linear regressions were used for building the first line of the calibration matrix.

For calibration in axis Mz, all forces and moments had high linearity, except the y axis. The axis My presented the largest variation in all axis. The Mz axis varied 207.2534mV. This resulted in a sensitivity de 10.166mV/Nm and a resolution of aproximately, 0.4803Nm. The Mz axis obtained a value of 23.0684% for histeresis and 14.90267% for nonlinearity. The values of angular coefficients of linear regressions were used for building the sixth line of the calibration matrix.

For the calibration in axis My, all forces and moments had high linearity, except x, Mx. The My axis presented a larger variation between all The axis, 5264.28138mV. This resulted in a sensitivity de 310.0845mV/Nm and a resolution of 0.01547Nm. The x axis obtained a value de 2.531215% for histeresis and 3.16978% for nonlinearity. The values of angular coefficients of linear regressions were used for building a fifth line of the calibration matrix.

It is evident that for a calibration in axis Mx, all forces and moments had high linearity, except the z axis and My. The Mx axis presented the bigger variation between all the axis. The Mz axis varied a total of 4262.12782mV. This resulted in a sensitivity of 233.7472mV/Nm and resolution of 0.0208Nm. The Mx axis obtained a value of 2.062381% for histeresis and 3.02202% for nonlinearity. The values of angular coefficients of linear regressions were used for building the fourth line of the calibration matrix.

Conclusion

There is a significant coupling between the My axis and x. This coupling happens because the strain gauges in the vertical surfaces are above the My strain gauges, generating torque. The sensitivity in the x axis is low, because the structure presents little elastic deformation, in order to prevent plastic buckling.

The sensitivity of this instrument is comparable to other systems in the literature [2, 13, 14].

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